valleys in the region. The Quaternary tectonism manifest in differential movements created depositional basins which were largely uncoeval. It is during this time that the Himalaya registered maximum upheaval of the order of 3–4 km (ref. 13).

The Ladakh and Lahaul-Spiti region exhibits various events of hot-humid and dry-cold climate in the last 35,000 years. The climatic changes were accompanied with advance and retreat of forest and steppe-type vegetal covers, as recorded by the Tsokar sediments between 30,000 and 9000 years B.P. The plant impressions and charcoal fragments in the basal part of Lamayuru indicate warm temperate climate up to around 30,000 years B.P., whereafter semiarid climate prevailed until about 1000 years B.P[7]. The presence of rock varnish in Ladakh suggests hot and dry climate in the Holocene (?).

The forest- and/or steppe-type vegetation with mild climate must have been favourable for the migration of humans up to the Indus valley in Ladakh. The charcoal pieces from a fire place on the Indus terrace has been dated 6710 ± 130 years B.P[14]. The Qinghai-Xizang region in the Tibet plateau likewise shows periodic occurrence of warm-moist and cold-dry climate during the past 10,000 years[15]. Lake cores of the brackish water Qinghai lake have indicated warm-humid and arid-cold periods during the last 13,000 years, the climatic fluctuation being mainly the result of Quaternary tectonic uplifts of the Tibetan plateau and Himalayan mountains[16]. It seems that in the Late Quaternary (particularly in the last recorded 35,000 years), atmospheric circulation changed dramatically due to strong but differential uplifts creating varying topographic highs and lows and the environment alternated sharply and frequently between cold-dry and hot-humid, so that forest- and steppe-type vegetation moved backward and forward.

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Quaternary deposits along the Indus Suture Zone and evolution of Himalayan rivers

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Quaternary deposits, found only in isolated basins behind the main great Himalayan crest-line and along the courses of the main rivers, are preserved only in isolated structural depressions scoured by valley glaciers because of rapid Quaternary uplift and attendant erosion. The Early Quaternary deposits rest unconformably on basement and are preserved only in the Chilas and Skardu areas of Baltistan, where they consist of a basal till overlain by fining upwards valley fill sequences. Palaeomagnetic reversal correlation suggests an earliest Pleistocene age. The Middle Pleistocene deposits seem to be absent. The early Pleistocene (or pre-Quaternary) is overlain at Leh and elsewhere, by a complex of tills and terraces associated with possibly the last three main glacial phases of the Late Pleistocene. The Quaternary events cannot ordinarily be disentangled from earlier Pleistocene events. Correlation is very difficult due to the isolation of most exposures and the lack of dateable sections.

Introduction

The Indus Suture Zone extends northwest from southeastern Tibet to Ladakh (Figure 1). Apart from studies of modern glaciers[1], little has been done on the

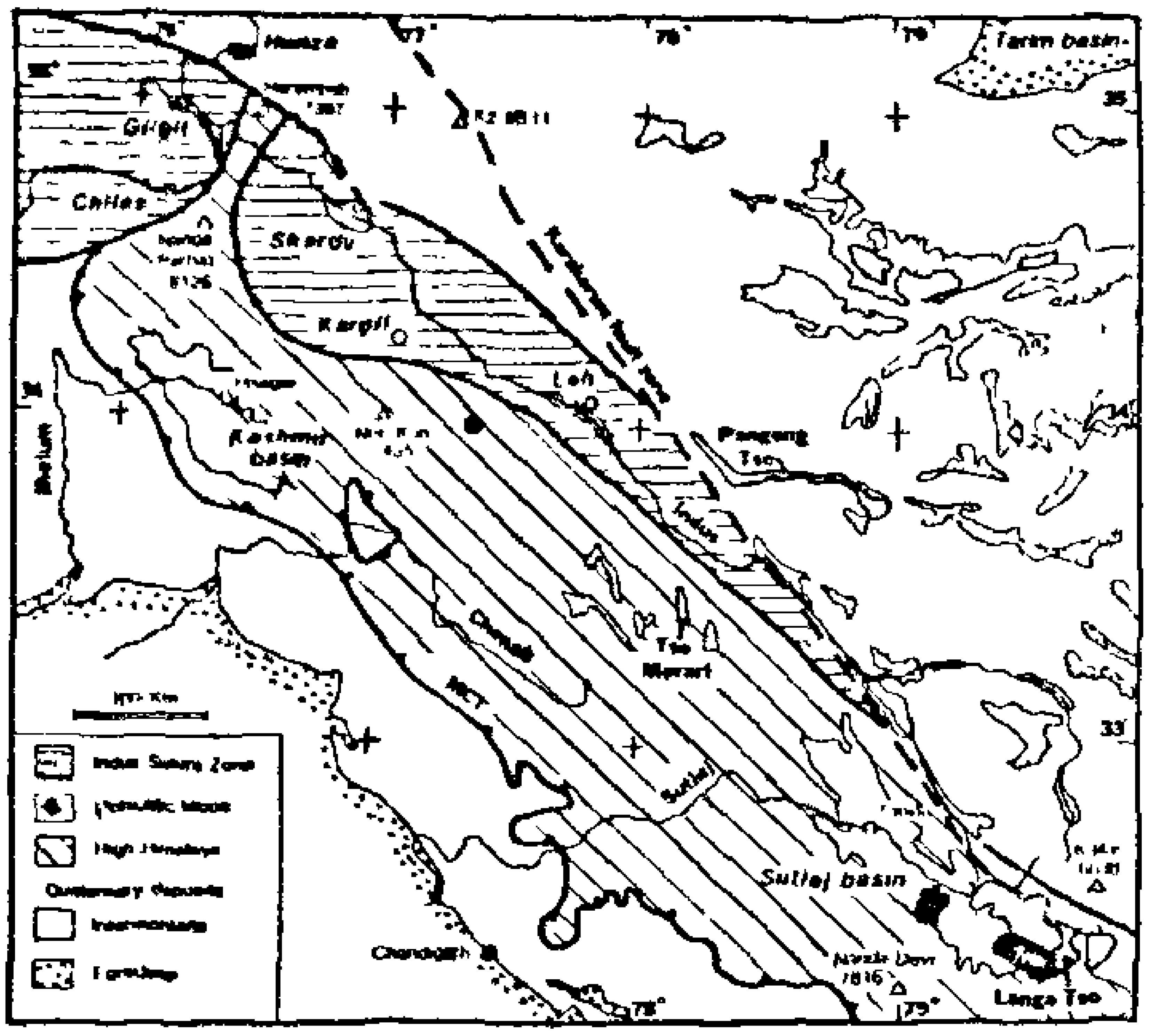

Figure 1. Distribution of Quaternary deposits in the NW Himalaya and adjacent areas (data from 1:500,000 Geological Map of Qinghai-Xizang Plateau, Science Press, Beijing, 1988).

Quaternary of this belt. More work has been done in the westward extension of the Suture Zone in Baltistan which, at present, must form the basis of a Quaternary history of the Suture Zone.

During the early Tertiary, India collided with Tibet along the Indus Suture Zone. Rivers draining the Ladakh-Transhimalaya magmatic arc on the north fed into a fore-deep on the deforming Indian margin on the south, depositing thick marine, then continental clastic sediments. During the Miocene, displacement shifted to the Main Central Thrust zone, isolating the original foredeep. The younger Tertiary and Quaternary history of the Indus Suture Zone is one of complex southward thrusting (and northward backsliding) and attendant tectonic uplift and erosion; interacting with major drainage changes and glaciation. Because of great uplift of at least 3 km since the mid-Miocene, little sediment is actually preserved along the Indus Suture Zone. Mostly the late Quaternary deposits are preserved only temporarily in terraces and erosional outliers. Hence, only the youngest Quaternary events can usually be studied in any detail. Furthermore, studies on the Quaternary deposits have been scarce. In Ladakh, early work on the river terraces and glacial deposits[2–4] has since been added to by the limited studies of Burgisser *et al.*[5] and Fort *et al.*[6–9]. However studies on terraces and gravels along the upper Satluj and Indus rivers in Tibet are very limited. The only comprehensive studies available relate to Baltistan[10] (Figure 1).

The stratigraphy and palaeoenvironments of the preserved Quaternary sections along the Indus, Gilgit and Hunza rivers in Baltistan are outlined here (Figure 2).

Baltistan

Chilas

An early glaciation is represented by the indurated lower Jalipur diamictites and upper Jalipur fluvio-glacial valley-fills[11], younger than 1–2 m.y., and tectonically deformed along the dextral-reverse Raikot Fault bounding the rapidly rising Nanga Parbat-Haramosh massif. The middle glaciation is represented by two diamictites interbedded with diverse sediments including thick lake-deposits—the lower Shatial diamictite recording the furthest advance of the Pleistocene glaciers down the Indus valley. The last main glaciation apparently postdates 140,000 years and consists of three to four separate advances which are defined by the moraine topography. Near Haramosh and downstream to Nanga Parbat, transverse glaciers and landslides have periodically dammed the Indus, forming lakes in which sediment accumulated. Catastrophic floods related to failure of these dams periodically swept coarse debris down the Indus and across the Punjab plains. In 1841 one such flood swept away a Sikh army camped at Attock over 350 km downstream[12]. The formation and disruption of these dams cause local aggradation and incision, forming well-marked terraces and incised valleys—sometimes on a large scale as demonstrated in the Skardu basin. Thus, isolated terraces and incised valleys cannot be used to infer or correlate glacial and interglacial phases.

Hunza valley

In the Hunza valley, the earliest glacial phase, attributed to the early Pleistocene, left isolated and deeply weathered erratics on summit surfaces above 4150 m. The succeeding phases occur at 2,500 m (older than 139,000 years) and lower. These lower elevations reflect valley incision during the Pleistocene and are related to uplift of the Karakorum[13]. If one assumes that the earlier glaciers reached around the same height, the early Pleistocene uplift of over 1500 m is then indicated. In the valley itself, a complex of eight glacial deposits is mostly younger than 150,000 years BP (ref. 14). Older deposits are not preserved.

The upland and valley-fill sequences north of Hunza seem to fit the Hunza sequence.

Sarku basin

A thick, isolated clastic sequence with glacial deposits rises over 1 km above the northern side of the present wide valley in Skardu[14]. This Bunthang sequence must have been deposited when the main valley was blocked by ice. Above a basal coarse diamictite, the lower unit consists of 50 m of micaceous sand passing up into

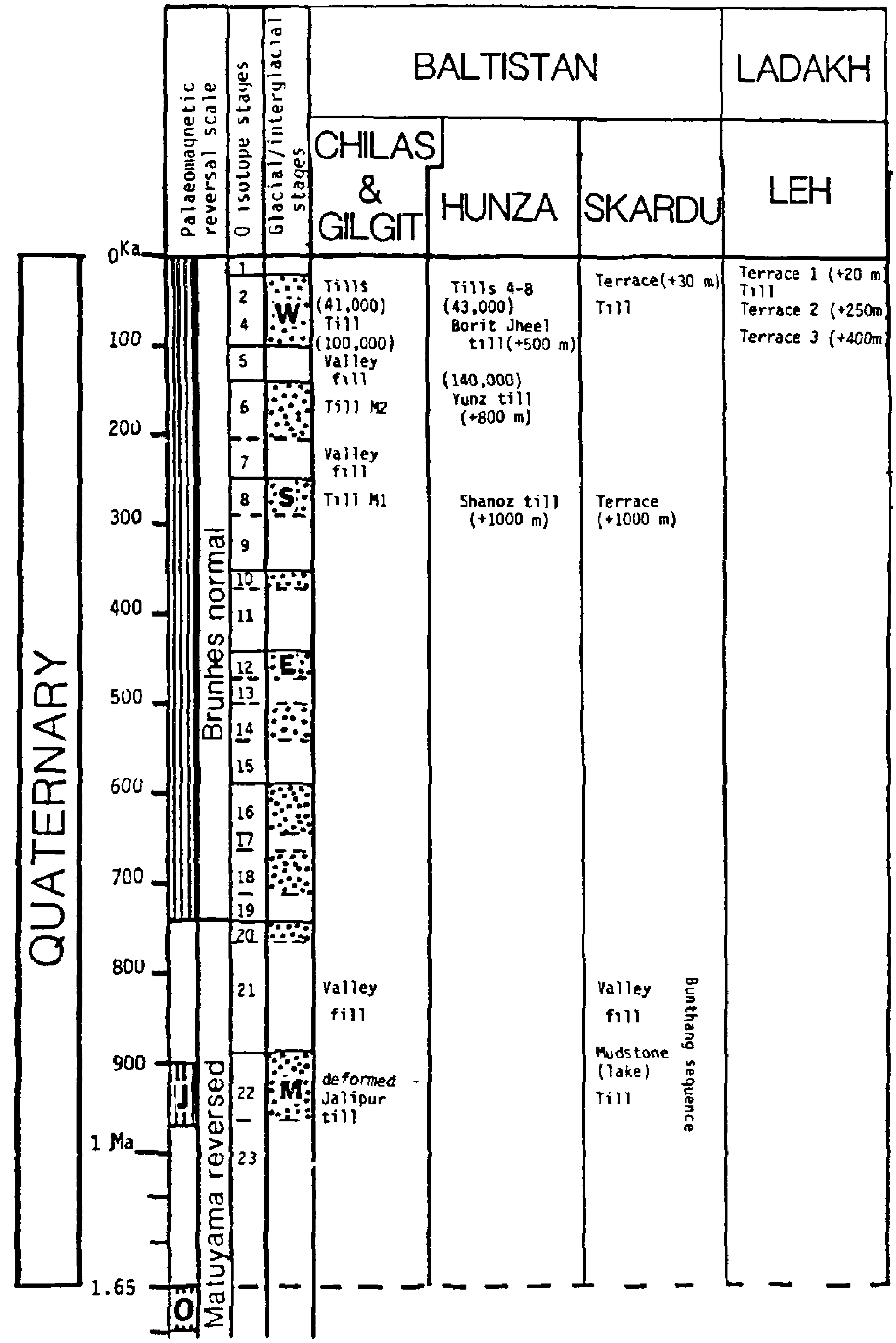

Figure 2. Correlation of Quaternary basins with standard time scale. Palaeomagnetic scale: normal events; J, Jamarillo; O, Olduvai. Glacial stages dotted: M, Menapian; E, Eemian; S, Saalian; W, Wurm. Dates in brackets are thermoluminescence ages with large errors: (+800 m)—heights of feature above present river level.

300 m of silty clays deposited in a glacial lake. The middle unit consists of 200 m of alluvial fan boulder conglomerates and interbedded sandstones which thicken towards the mountain front to the northeast. The upper unit onlaps underlying inclined fanglomerates and consists of up to 70 m of mixed sand, silt and clay deposited by longitudinal streams and associated lakes. The entire sequence is cut by a terrace over 1000 m above the present Indus river. This terrace is overlain by thick loess deposits and long predates the last ice advance into the Skardu valley, since the deposits were eroded and sculptured by this advance. No fossils have been found in the Bunthang sequence. But the lower and upper sequence are reversely

magnetized throughout and were probably deposited during the Matuyama reversed chron in the latest Pliocene–early Pleistocene (between 2.48 and 0.73 m.y.). The entire sequence could have been deposited in less than 500,000 years.

The western end of the Skardu basin is blocked by a now breached moraine dam, behind which lake deposits accumulated during the post-glacial retreat of the glaciers out of the Skardu basin. Younger moraine dams and lakes occur at higher levels in side valleys and probably mark successive stillstand phases during historic times.

Sedimentary sequences occur further upstream from Skardu, notably at Khapalu. But none of these areas has been studied until the Indus valley at Leh is reached.

Ladakh

Upstream, terraces occur all along the Indus river in Ladakh. Extensive deposits are confined to the broader areas at Kargil and Leh where the valley broadens out. Near Leh three so far undated main terraces, related to three main glacial phases, have been identified[6] (Figure 3). The lowest terrace at +20 m is a simple alluvial or rock terrace related to the present river. The second terrace between +200 and +250 m consists of coarse alluvial fan conglomerates presumably related to periglacial fan advance. It is occasionally overlain by moraine from a glacial advance. The third terrace lies about 50 to 100 m above the second terrace. Extensive lateral migrations of the Indus River across the valley have controlled the local base level and terrace formation on the adjacent fans.

Lake sediments have accumulated in places where glaciers or landslides have blocked valleys. Most of these seem post-glacial or historic in age, but some are overlain by supposed glacial moraines. A simple correlation is shown on Figure 2 where the terraces T3 and T2 are interpreted as successive interglacial valley fills, following advance of a valley glacier westwards along the Indus. The youngest phases of glacial retreat are recorded in the Nimaling area, northwest of Tso Morari (Figure 1). Quaternary deposits occur around Tso Morari and elsewhere in Ladakh.

Satluj basin

The Satluj basin is a pull-apart structure related to Miocene and younger right-lateral movements on the Karakorum Fault[15]. Thick clastic deposits lie in an extensive (6000 km) basin along the upper Satluj (Xiangquan) River (Figure 1) and consist of coarse-grained gravels with rounded pebbles and boulders interbedded with sands and silts[16]. Around Zanda they overlie late Tertiary lake deposits and contain Pliocene vertebrates[17]. However, no Quaternary deposits have been described. In post-glacial times, canyons up to 1000 m deep have been cut into these deposits by the Satluj River and its tributaries. It is obvious from the river courses and gradients that the present lower Satluj has in fact cut back by headward erosion and truncated a formerly longitudinal drainage system. Elsewhere (e.g. in the Tashkurgan valley), the present courses of the rivers are due to glacial meltwaters carving deep canyons across ranges once marginal to glacier-filled

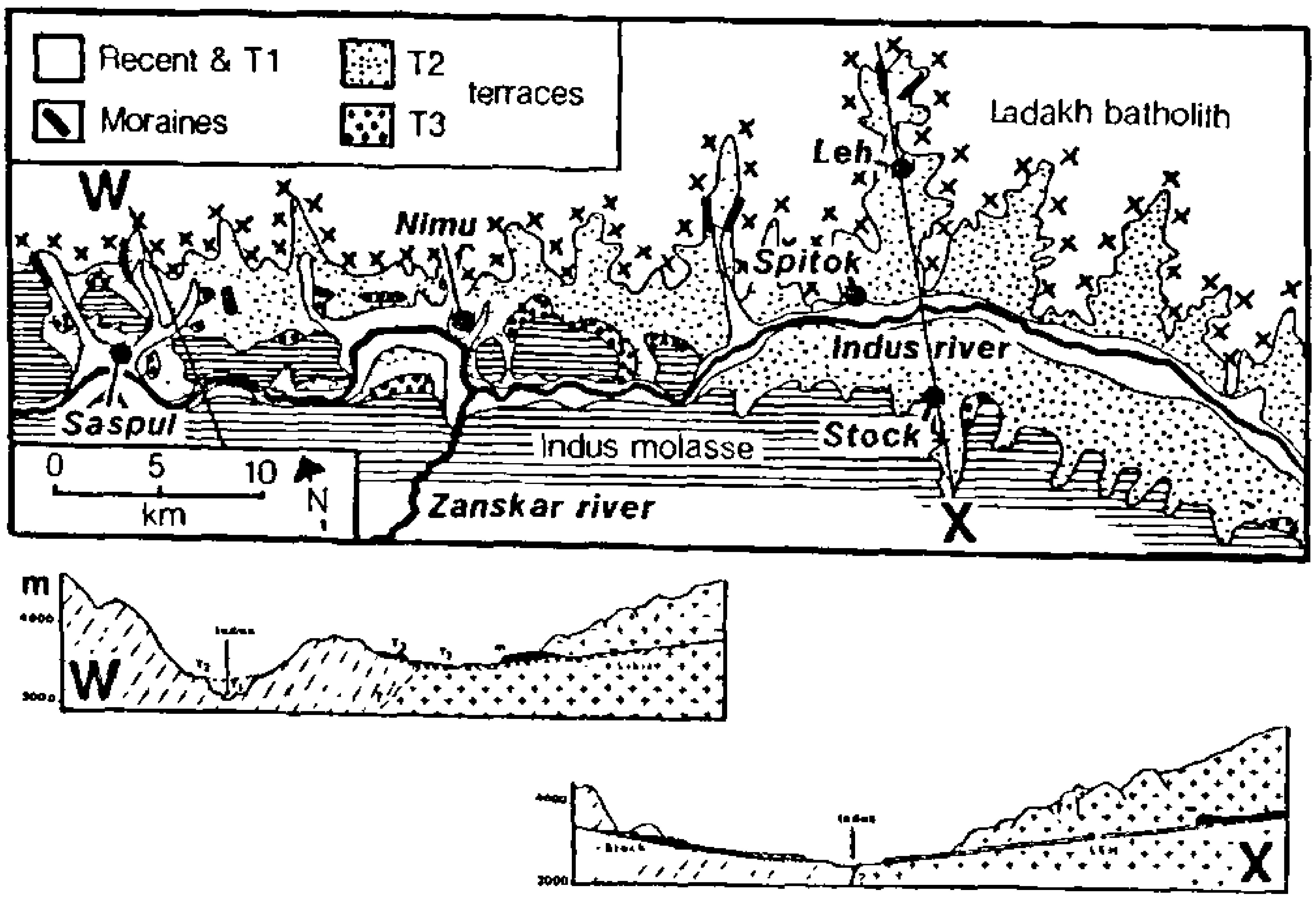

Figure 3. Quaternary map and sections around Leh, Ladakh (modified from Fort[8]).

longitudinal valleys. Ice retreat left curious drainage patterns whereby rivers turn at right angles out of gentle open valleys to carve their way through high and impenetrable mountain ranges. This is *not* explainable by consequent drainage across slowly rising mountains.

Evolution of Himalayan Rivers

The evolution of Himalayan river systems is an old and controversial subject[18]. Many of the old interpretations which were disregarded in the middle 20th century can now be resurrected in a plate tectonic framework. Several interesting and peculiar features are seen.

Three of the largest rivers, the Indus, Tsangpo and Satluj, rise close together near Mount Kailas (Figure 1) and flow in divergent directions. The Indus and Tsangpo flow in opposite directions within a trough roughly corresponding to the Indus Suture Zone before turning south at the northwestern and northeastern syntaxes, and cutting directly across the Himalayan ranges. In the northwest, a line of depressions along the Karakorum Fault connects up with the Tashkurgan valley and eventually with the north Pamir.

Many of the tributaries of both the Indus and Tsangpo join the main rivers with the acute angle pointing east. That is, the tributaries look as if they are joining *westward*-flowing rivers. This is true for the Indus, but not for the Tsangpo, which flows east.

It looks as if a large river which flowed westwards in the Indus Suture trough has been chopped into several sections. Part of this can be explained by headward erosion of streams draining the southern slope of the Himalaya: but not all of it. Much of the disruption and the present sluggish, choked upper courses of the major rivers can be related to glacial damming and glacial advance into the Indus trough during Quaternary glaciations. Much of the peculiar alternation of deeply aggrading braided reaches and turbulent rapids can be explained in the same way.

Most of the large southward flowing rivers, like the Satluj, rise north of the high peaks and cut deep transverse gorges across the range. They do not, however, cut into or bend the linear watershed boundary—which they would have done if they had simply captured their headwaters from across the range. This peculiarity and others can now be readily explained with plate tectonic concepts of collision orogenesis.

As the Himalaya is thrust southwards, uplift and frontal erosion are in balance and this uplift causes progressive northward diversion of the major rivers. Thus, parts of the Indus and Tsangpo drainage are now exceedingly complex, as overflow over low divides took them via circuitous routes along old rifts, faults and valleys on the Tibetan plateau behind. Many of these diversions must have been promoted by the northward advance of glaciers from the rising Himalaya and their consequent blocking of the drainage immediately north of the Himalaya.

The evolution of the Himalayan rivers is a complex interaction between primary structural control modified in the Quaternary by glacial damming, diversion and headwater capture.

Conclusions

Relatively little is known of the Quaternary history of the Himalaya due to the rapid uplift and consequent erosion of most of the evidence. What little evidence there is suggests that at least one major early Pleistocene glacial advance was followed by erosion during the middle Pleistocene. Only in the late Pleistocene were glacial and interglacial deposits locally preserved in glacially scoured rock basins along the major rivers. The combination of uplift and glacial blocking and diversion of rivers has greatly modified the geomorphology and drainage systems of the Himalaya and Tibetan plateau.

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